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Validation of the wind erosion stochastic simulator (WESS) and the revised wind erosion equation (RWEQ) for single events

R.S. Van Pelt [a,*], T.M. Zobeck [b], K.N. Potter [c], J.E. Stout [b], T.W. Popham [d]

[a] *USDA-ARS-Wind Erosion and Water Conservation Research Unit, 302 W. I-20, Big Spring, TX 79720, USA*
[b] *USDA-ARS-Wind Erosion and Water Conservation Research Unit, 3810 4th Street, Lubbock, TX 79415, USA*
[c] *USDA-ARS-Grassland Soil and Water Research Lab, 808 E. Blackland Road, Temple, TX 76502, USA*
[d] *USDA-ARS-South Plains Area, 1302 N. Western Road, Stillwater, OK 74075, USA*

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Abstract

The wind erosion stochastic simulator (WESS) is a single event wind erosion model that is the core of the wind erosion submodel of the environmental policy integrated climate (EPIC) erosion model. WESS uses inputs of soil texture, erodible particle diameter, soil roughness, soil water content, crop residue, and 10 min average wind speeds to predict the erosion at several user-selected distances within a given field. The revised wind erosion equation (RWEQ) makes annual or period estimates of wind erosion based on a single event wind erosion model that includes factors for wind and rainfall, soil roughness, the erodible fraction of soil, crusting, and surface residues. In this study, we compared estimates of wind erosion at multiple points in a field for 24 events at Big Spring, Texas with the predictions of WESS and compared estimates of maximum sediment transport capacity (Qmax), critical field length at which Qmax is attained (*S*), and soil loss (SL) calculated from field measured data collected at six locations and 41 events with the predictions of RWEQ. Compared to observed estimates of erosion for the 24 events, WESS under-predicted 9 events, accurately predicted 8 events, and over-predicted 7 events. In general, RWEQ underestimated Qmax and SL and overestimated *S*.

Keywords: Wind erosion; Soil loss; Predictive models; RWEQ; WESS; EPIC

Software availability

Name of software: Revised wind erosion equation (RWEQ)
Developer: USDA-ARS-SPA-CSRL-Wind Erosion and Water Conservation Research Unit, 3810 4th Street, Lubbock, TX, USA. Tel.: +1-806-749-5560; fax: +1-806-723-5272; e-mail: tzobeck@lbk.ars.usda.gov
Year first available: 1998
Hardware required: IBM compatible PC with 80386 and 80387 with 4 MB RAM
Software required: MS-DOS version 5.0 or laterProgram language: Watcom CProgram size: 3 MB
Available free from: http://www.csrl.ars.usda.gov/wewc/rweq.htm

Name of software: Wind erosion stochastic simulator
Developer: Dr Jimmy Williams, 808 East Blackland Road, Temple, TX 76502, USA. Tel.: +1-254-774-6124; fax: +1-254-770-6561; e-mail: williams@brc.tamus.edu
Year first available: 1994
Hardware required: IBM compatible PC with 80386 and 80387 with 8 MB RAM
Software required: MS-DOS version 5.0 or later
Program language: Fortran 77
Program size: 1 MB
Available free from: williams@brc.tamus.edu

1. Introduction

The global change and terrestrial ecosystem soil erosion network (GCTE-SEN, 1996) has recently conducted a model validation exercise for water erosion models.

* Corresponding author. Fax: +1-432-263-3154.
E-mail address: svanpelt@lbk.ars.usda.gov (R.S. Van Pelt).

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Several models are also available to estimate wind-induced soil erosion, but few studies have been conducted to validate these models using field measured data. In this study, as part of a larger cooperative GCTE-SEN project, we evaluate how well estimates of erosion made with the wind erosion stochastic simulator (WESS) and the revised wind erosion equation (RWEQ) compare with data collected in eroding fields.

The environmental policy integrated climate model (EPIC) has been used to evaluate policy effects on soil erosion. WESS, the wind erosion module of EPIC, is a process-based model that uses local wind speed data and a stochastic wind speed perturbation factor along with soil surface data including soil texture, percent erodible ($<$0.84 mm) fraction, soil surface moisture and drying rate, erodible soil thickness, surface soil bulk density, and soil surface roughness parameters of large aggregate size (random roughness) and ridge height and spacing (oriented roughness) to predict wind erosion on an event-wise or periodic basis for user-specified distances from protected surface (DPS) within a field. Recently, WESS was successfully evaluated against observed estimates of erosion from a clay loam soil for several wind events in Alberta, Canada (Potter et al., 1998). This study was conducted for a single season and surface roughness and vegetative cover did not vary sufficiently during the period of investigation to assess the effectiveness of the model under soil surface conditions other than those noted in the publication.

USDA Agricultural Research Service (ARS) scientists and engineers have recently released RWEQ (http://www.csrl.ars.usda.gov/wewc/rweq/readme.htm). RWEQ makes annual or period estimates of wind erosion based on a single event wind erosion model that includes factors for wind and rainfall, soil roughness, the erodible fraction of soil, crusting, and surface residues (Fryrear et al., 1998a, 1998b). A previous test of 11 wind erosion events found the correlation between observed and estimated maximum transport capacity (Qmax) which is the maximum amount of sediment that can be entrained by the wind, critical field length (*S*) which is the distance at which Qmax is attained, and field soil loss (SL) to be 0.82, 0.29, and 0.97, respectively (Fryrear et al., 1998a).

Wind erosion research and modeling (WERM) efforts conducted by the ARS over the last decade have necessitated the collection of several large bodies of wind erosion and weather data from many diverse locations in the US. This effort has been facilitated by the development of technology and equipment that have enabled the measurement of wind erosion losses on storm event basis (Fryrear, 1986; Stout and Zobeck, 1996). The availability of field measurements has improved the description of erosion losses across a field (Stout, 1990) and also permits the validation of wind erosion models. We tested RWEQ and WESS against much of the aforementioned body of data in order to determine the accuracy of their predictions.

2. Methods

Six sites from five states across the US were chosen to validate RWEQ (Table 1). Individual storm event data from only the Big Spring, Texas location (24 storms during 7 years of data collection) were used to validate WESS. The sites were described, instrumented, and the erosion data collected by USDA-ARS and USDA-NRCS personnel. All the sites were a 100 m radius circular field (~2.5 ha) outfitted with a weather station and 13 erosion sampling stations (Fryrear et al., 1991). Weather data collected included instantaneous rainfall (mm), 2 m wind speed (m s^{-1}) and direction averaged over 1-min intervals and air temperature (°C), relative humidity (%), 0.1 m soil temperature (°C), and solar radiation (W m^{-2}) averaged over 10-min intervals. For the purpose of validating WESS and RWEQ, the wind speed data were averaged over 10-min intervals. Soil surface condition data including soil tillage ridge height and spacing, aggregate or random roughness, percent erodible ($<$0.84 mm) surface soil fraction, and standing and flat plant residues were collected several times a season. The frequency of soil surface data collection differed by location and year and was determined by weather-induced changes in the surface characteristics.

Soil saltation and suspension loads at each of the 13 field sampling stations were estimated by taking the weight of sediment collected in individual Big Spring Number Eight (BSNE) sampler clusters at those sampling stations and calculating the transport load ($Q(x)$) (kg m^{-1}) (Fryrear and Saleh, 1993). Creep load was estimated for each of the 13 sampling stations in a similar manner based upon transported soil weights collected in soil creep samplers at four separate sampling stations in the field. Field soil loss (SL) (kg m^{-2}) for each event was calculated using soil transport estimates from selected sampling stations across the field. Details for the calculation of soil loss are presented by Fryrear et al. (1998b). Since the field erosion observations are calculated estimates based upon actual measured observations, we will refer to the erosion data as observed estimates.

WESS simulations were run for the dates of 24 storm events in the 7 years of erosion observations at Big Spring, TX. The time period between field sampler servicing was rounded to the nearest multiple whole day and the 10 min average wind data for that event was input along with the soil surface conditions reported for the site on that date. Soil roughness was calculated according to Potter and Zobeck (1990), when pin roughness data were available and was estimated by comparing chain roughness data with surface photographs when only chain roughness data were available. Initial soil

Table 1
Test site surface soil characteristics

Location	ID	Texture	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Calcium carbonate (%)	Number of tests (%)
Kennett, MO	KMO	Sand	90.0	7.1	2.9	0.72	0.2	6
Big Spring, TX	BSP	Loamy sand	83.6	8.4	8.0	0.29	0.0	25
Mabton, WA	MWA	Loamy sand	82.3	12.8	4.9	0.76	0.0	4
Sidney, NE	SNE	Loam	39.8	42.9	17.4	2.34	0.0	3
Prosser, WA	PWA	Silt loam	44.2	50.1	5.7	1.14	0.0	2
Eads, CO	ECO	Clay loam	29.3	38.6	32.1	1.59	1.0	1
								Sum = 41

moisture conditions were inferred from rainfall and temperature data for each event. The simulations for each event were run at DPS that coincided most closely with the DPS of field sampling stations as these distances varied with the mean wind direction of each event.

RWEQ simulations were run for 41 storm events at six locations across the US. The locations, soil characteristics, and number of events at each location are presented in Table 1. RWEQ uses a number of input factors to estimate the maximum transport capacity (Qmax), the critical field length at which Qmax is attained (S), and soil loss (SL). The wind factor (WF), erodible fraction (EF), surface crust factor (SCF), oriented and random soil surface roughness (K'), and crop on the ground factor (COG) were determined for each erosion event. The details of the procedures used to determine these values are described by Fryrear et al. (1998a, 1998b). The WF for each estimated storm was computed from 10-min wind speed measurements averaged for the entire 24 h day (Fryrear et al., 1998a). EF was determined for each location by dry sieving surface soil samples (Chepil, 1962). SCF was defined as a function of percent clay and organic matter (OM) content (Eq. (1)).

$$\mathrm{SCF} = 1/(1 + 0.0066(\mathrm{clay})^2 + 0.21(\mathrm{OM})^2) \quad (1)$$

K' was determined using measured roughness parameters and the amount of flat and standing residue were used to estimate COG (Fryrear et al., 1998b). Since the EF, K' and COG factors were often measured only two or three times per season, interpolative estimates of these factors based upon weather events were often necessary. Degradation of aggregates and roughness were estimated using cumulative rainfall and linear interpolation between measurement dates was used to estimate COG.

Relatively simple equations (Eqs. (2) and (3)) are used to estimate Qmax and S in RWEQ (Fryrear et al., 1998b).

$$\mathrm{Qmax} = 109.8(\mathrm{WF}*\mathrm{EF}*\mathrm{SCF}*K'*\mathrm{COG}) \quad (2)$$

$$S = 150.71(\mathrm{WF}*\mathrm{EF}*\mathrm{SCF}*K'*\mathrm{COG})^{-0.371} \quad (3)$$

The Qmax and S calculated using Eqs. (2) and (3) are called the estimated Qmax and S, respectively in the remainder of this paper.

The observed estimates of soil loss (SL) for each event were taken from the storm data sheets that were a part of the WERM data analysis package. SL changes with distance across the field and so the equation that estimates soil loss cannot be stated as simply as Eqs. (2) and (3). A finite difference equation that approximates the governing equation (Eq. (4)) is used in RWEQ to estimate SL at different points in a field defined by x = DPS with s being the critical field length (Fryrear et al., 1998b).

$$\mathrm{SL} = (2x/s^2)\mathrm{Qmax}(\exp(-(x/s)^2)) \quad (4)$$

The finite difference element used in RWEQ is a 10 m wide strip and the soil loss estimates for each strip are multiplied by strip length and summed to estimate total field soil loss.

3. Results and discussion

WESS was used to predict the erosion resulting from 24 of the individual wind events at Big Spring, TX during the 7 years that wind erosion data was collected at this location. When an accuracy criterion of ±50% of the observed values at DPS from 60 to 140 m was used, WESS under-predicted 9 events, accurately predicted 8 events, and over-predicted 7 events. In general, the events that WESS under-predicted were large magnitude storms with observed erosion estimates >1.0 kg m^{-2} and the events that WESS over-predicted were small storms with observed estimates <0.2 kg m^{-2}. WESS gave the most accurate predictions for events that had observed estimated erosion from 0.2 to 1.0 kg m^{-2}. Since the large magnitude storms, some of which had observed estimates of greater than 5.0 kg m^{-2} at distances greater than 60 m from protected surface, have a much larger effect on annual erosion than the small storms, it is evident that WESS would tend to under-predict erosion on an annual basis. We used a storm of moderate intensity to ‘train’ the model and to set input factors such as the

Table 2
Input data, estimated and calculated maximum transport, critical field length and soil loss by test sites

Site H	Date	Input data I					Calculated Qmax	Estimated Qmax	Calculated S	Estimated S	Calculated SL	Estimated SL
		EF	WF	SCF	K'	COG	kg/m	kg/m	m	m	kg/m^2	kg/m^2
BSP	4/22/89	0.57	5.19	0.70	0.54	0.63	93.4	78.0	31.0	171.1	0.65	0.42
BSP	4/23/89	0.57	4.30	0.70	0.55	0.62	101.7	64.5	31.0	183.6	0.70	0.35
BSP	1/22/90	0.58	0.20	0.70	0.99	0.84	63.8	7.5	278.9	407.2	0.11	0.04
BSP	1/24/90	0.63	6.81	0.70	0.99	0.84	378.7	272.8	108.2	107.5	2.05	1.46
BSP	1/26/90	0.63	3.70	0.70	0.98	0.84	99.1	146.6	32.0	135.4	0.68	0.79
BSP	2/12/90	0.41	3.99	0.70	0.98	0.88	58.7	109.6	31.0	150.8	0.41	0.59
BSP	3/12/90	0.41	11.64	0.70	0.98	0.95	110.3	93.1	33.1	98.5	0.76	1.85
BSP	3/14/90	0.41	11.84	0.70	0.98	0.95	540.0	352.0	138.9	97.8	2.39	1.89
BSP	4/2/93	0.61	3.85	0.70	0.62	1.00	626.3	112.1	72.9	149.5	3.99	0.60
BSP	3/17/94	0.59	0.51	0.70	0.85	0.92	32.4	17.9	31.0	295.5	0.22	0.10
BSP	3/18/94	0.59	0.19	0.70	0.85	0.92	15.6	6.8	66.6	423.0	0.10	0.04
BSP	3/22/94	0.59	1.39	0.70	0.85	0.93	58.8	49.6	51.0	202.4	0.40	0.27
BSP	03/24/1994S	0.59	0.15	0.70	0.85	0.94	9.3	5.3	81.0	465.4	0.06	0.03
BSP	3/24/94	0.59	0.63	0.70	0.85	0.94	56.4	22.6	34.2	271.1	0.39	0.12
BSP	4/7/94	0.59	2.03	0.70	0.85	0.98	93.9	76.4	43.0	172.4	0.64	0.41
BSP	4/15/94	0.59	3.54	0.70	0.82	0.92	231.5	121.3	32.4	145.2	1.60	0.65
BSP	04/25/1994S	0.59	3.19	0.70	0.82	0.94	39.9	111.7	31.0	149.7	0.28	0.60
BSP	4/25/94	0.59	6.41	0.70	0.82	0.94	842.1	224.5	53.9	115.6	5.62	1.20
BSP	2/10/95	0.70	2.39	0.70	0.73	0.84	178.4	78.5	198.9	170.6	0.51	0.42
BSP	3/22/95	0.73	1.12	0.70	0.70	0.67	26.6	29.2	31.0	246.4	0.18	0.16
BSP	1/23/96	0.60	3.20	0.70	0.60	0.95	3.2	84.3	31.0	166.2	0.02	0.45
BSP	2/14/96	0.60	1.76	0.70	0.60	0.88	1.2	43.1	120.0	213.2	0.01	0.23
BSP	3/5/96	0.60	2.71	0.70	0.67	0.63	20.0	52.7	308.9	197.8	0.03	0.28
BSP	4/29/97	0.61	3.81	0.70	0.69	0.97	170.2	118.5	82.5	146.5	1.05	0.64
BSP	5/2/97	0.61	2.86	0.70	0.69	0.97	351.3	89.8	138.9	162.4	1.55	0.48
ECO	4/28/91	0.26	12.36	0.13	0.79	0.50	16.5	17.8	0.0	296.1	0.11	0.10

KMO	3/7/93	0.86	0.58	0.94	0.75	0.55	24.5	21.3	275.9	276.8	0.04	0.11
KMO	3/13/93	0.86	16.46	0.94	0.75	0.54	572.8	587.7	138.9	80.9	2.53	3.15
KMO	4/4/93	0.88	1.50	0.94	0.85	0.47	26.1	55.1	263.0	194.7	0.05	0.30
KMO	5/8/93	0.91	1.12	0.94	0.87	0.38	111.5	34.9	298.9	230.6	0.17	0.19
KMO	3/23/94	0.91	1.56	0.94	0.76	0.25	4.0	27.9	31.0	250.7	0.03	0.15
KMO	4/2/94	0.91	0.60	0.94	0.76	0.24	4.8	10.2	31.0	364.4	0.03	0.05
SNE	11/7/89	0.35	13.53	0.32	0.20	0.42	1.1	14.0	31.0	323.7	0.01	0.08
SNE	1/8/90	0.35	15.90	0.32	0.20	0.40	151.3	15.6	308.9	311.1	0.21	0.08
SNE	3/15/90	0.46	52.20	0.32	0.51	0.36	6.0	154.4	148.5	132.8	0.02	0.83
MWA	2/19/91	0.49	16.26	0.85	0.60	0.21	191.6	93.7	85.4	159.8	1.17	0.50
MWA	4/5/91	0.72	4.80	0.85	0.59	0.16	195.3	30.1	258.9	243.6	0.37	0.16
MWA	4/9/91	0.73	8.70	0.85	0.59	0.15	106.3	53.0	81.0	197.5	0.66	0.28
MWA	4/24/91	0.79	2.72	0.85	0.56	0.14	2.3	15.4	80.0	312.7	0.01	0.08
PWA	9/24/92	0.74	10.78	0.81	0.30	0.40	21.6	84.3	51.0	166.2	0.15	0.45
PWA	10/1/92	0.74	1.07	0.81	0.30	0.40	0.8	8.4	90.3	391.9	0.01	0.04
Minimum		0.26	0.15	0.13	0.20	0.14	0.78	5.26	0.00	80.86	0.01	0.03
Maximum		0.91	52.20	0.94	0.99	1.00	842.1	587.7	308.9	465.4	5.62	3.15
Mean		0.62	6.04	0.71	0.71	0.67	137.5	87.6	104.0	219.0	0.78	0.52
Standard deviation		0.16	14.08	0.18	0.22	0.28	204.8	115.8	91.4	95.8	1.21	0.62

Site H: BSP=Big Spring, TX; ECO=Eads, CO; KMP=Kennett, MO; SNE=Sidney, NE; MWA=Mabton,WA; PWA=Prosser, WA.Input data I: EF=Soil Erodible Fraction; WF=Wind Factor, SCF=Surface crust factor; K'=Roughness parameter; COG=Crop on ground factor; Qmax=Maximum transport capacity; S=Critical field length; SL=Soil loss.

stochastic perturbation factor for instantaneous surface wind speed. Recent research indicates that the variability of wind speed at the surface increases as the wind speed measured at the 2 m height increases (Van Pelt et al., unpublished data). The accuracy of WESS might be increased by incorporating a dynamic stochastic perturbation factor for surface wind speed driven by 2 m wind speed into the model rather than relying on the static value that must now be chosen and input by the user.

Plots of the comparisons between WESS predicted erosion and observed estimated erosion for 4 events at Big Spring, TX are presented in Fig. 1. The plot for the 4/22/89 event shows paired observed estimates with low variability and the relatively high accuracy of prediction for this event. The plot for the 4/25/94 event shows observed estimates with low variability and the typical under-prediction for large events. Both of these plots show the inability of WESS to accurately predict erosion rates at DPS of less than 60 m. Although this source of error would become increasingly insignificant as field size increases, it does point out a problem either with the use of transport load to estimate erosion rates or with the form of the equation used by this and other models to predict the erosion rate. Modern advances in laser imaging and measurement of microtopography could be used in conjunction with aeolian transport samplers to reach a more thorough understanding of the relationship between aeolian transport and actual surface deflation for increasing DPS within eroding fields.

Plots for the 1/29/90 and 2/12/90 events demonstrate another problem with prediction of wind erosion. These two events occurred 14 days apart, there was no rain or other change in surface conditions between the events, the wind speed and duration were nearly identical, WESS predicted similar erosion curves, and yet there is a great difference in the observed estimated erosion. There was a 150° shift in wind direction between the storms, but the observations were made in a circular field in a broad open area. In spite of the sophistication of our data collection and predictive models, there are probably sources of variability in any field that we may not ever be able to accurately quantify and predict at such small spatial scales.

A summary of the results comparing RWEQ predicted values of wind erosion with observed estimates is presented in Table 2. Although the input data represented a wide range over all, some locations had little or no variation in some of the input data values. In general, RWEQ underestimated Qmax and SL and overestimated *S*. Close inspection of the data by location revealed that the estimates were not consistently higher or lower for most of the locations. Observed estimates for Qmax and SL were higher than RWEQ predictions in about 58% of the cases investigated while observed estimates for *S* were higher than RWEQ predictions in only 22% of the events analyzed.

Simple linear regressions of observed estimates vs. RWEQ predictions of Qmax, *S*, and SL revealed significant ($P < 0.05$) correlations for Qmax and SL with correlation coefficients of 0.70 and 0.62, respectively. The observed estimates of *S* were not significantly correlated to RWEQ predictions. Fig. 2 illustrates the relationship of the observed estimates and RWEQ predictions of Qmax for all storm events investigated. In general, RWEQ predicted from 40% to 70% of the observed estimates of Qmax. The relation of observed estimates and RWEQ predictions of SL is presented in Fig. 3.

The results of the investigation with RWEQ are very encouraging. Erosion was measured at locations that varied considerably with respect to soil, climate, and wind patterns and yet the RWEQ predictions were correlated within an order of magnitude of the observed esti-

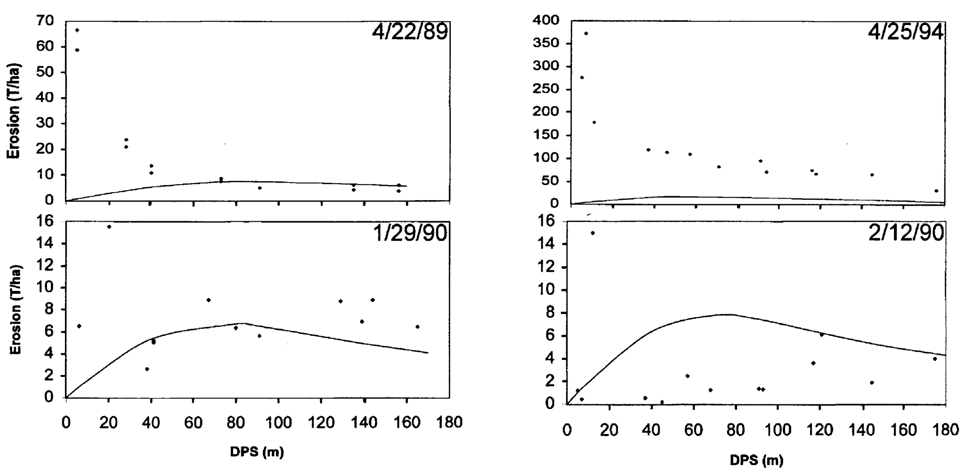

Fig. 1. Plots of WESS predicted (solid lines) vs. observed estimated erosion (diamonds) by distance from protected surface (DPS) for four selected storm events at Big Spring, TX.

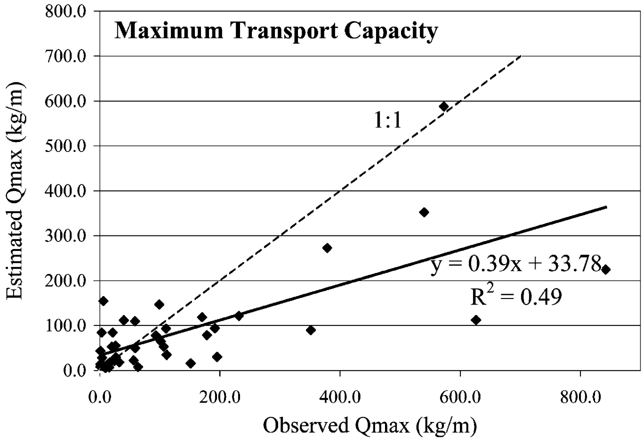

Fig. 2. Relation of observed estimated and RWEQ predicted Qmax for 41 wind erosion events.

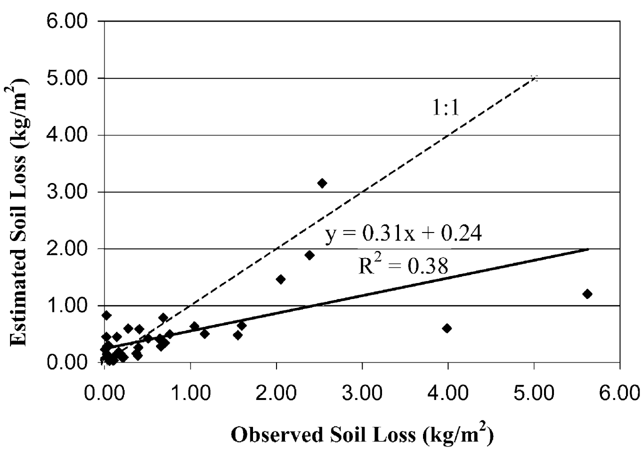

Fig. 3. Relation of observed estimated and RWEQ predicted SL for 41 wind erosion events.

mates. Observed estimates and RWEQ predictions of *S* were not significantly correlated, suggesting that either the concept of critical field length is more complex than currently represented in RWEQ or that the 100 m radius field were not sufficiently large for accurate measurement of this factor. Much like WESS, RWEQ tended to overestimate SL in low magnitude events and underestimate SL for large magnitude events (Fig. 3). The same trend may be observed for RWEQ estimates of Qmax in Fig. 2. RWEQ uses a stochastic wind speed perturbation factor based on the Weibull distribution of local wind speeds that is part of the weather data input file. In practical use, this factor to vary wind speed works very much like the factor we used in WESS, where we chose the factor based on an average storm. It is likely that the inclusion of a secondary perturbation factor based upon the 2 m wind calculated by the first perturbation factor, or in our case, the input wind speed data would improve the agreement between observed and estimated values for SL and Qmax.

4. Conclusions

For both models investigated, there are many possible explanations for the variation in the differences between the model predictions and the observed estimates. The input factors listed in Table 2 were often measured many weeks before or after an erosion event and they were measured using various methods. Measurements taken just prior to an erosion event would probably improve the model predictions. Additionally, the soil erodibility and erodible thickness parameters used in WESS and the EF used in RWEQ would be difficult to quantify given the spatial variability of the mantle of sandy abrader material that is often deposited on the soil crust after an intense rain event. The exact period of the erosion events was also difficult to quantify. For RWEQ, WF was calculated on a daily basis and erosion events occasionally started before midnight of the day of record. Thus, more erosion occurred than the WF of record and periods of erosion recorded in the field notes considered. For both models, the trend of overestimation for small magnitude events and underestimation of large magnitude events points to the need for a more dynamic stochastic wind speed perturbation factor that would be a function of the estimated or actual wind speed data that are used for input parameters. Finally, the very frequent failure of WESS estimates of erosion to converge with observed estimated erosion at distances of less than 60 m from the upwind protected surface would indicate that either the algorithms used to predict erosion at different distances from protected surface or the concept of using mass transport to estimate erosion may be flawed. Considering the temporal and spatial variability of soil surface characteristics, the random nature of turbulence, and the temporal and spatial variability of wind-induced soil movement, it is unlikely that models will ever yield estimates that will exactly match the field observations for a given event.

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